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L.K. Domansky et al

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COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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On the basis of major experimental work and with the use of modern methods of calculating temperature regimes in dams, scientifically justified methods of planning hydrotechnical installations have been worked out for the Far North; basic principles have been established for the design of both earth and concrete dams; and engineering procedures have been introduced that make it possible to work year-round on dam construction. The construction of many dams with various heads has yielded a great deal of experience and proved the over

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Dam design and construction in the northern USSR and Siberia

by

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Nearly half the area of the whole USSR, including the northern European part and most of Siberia and the Soviet Far East, has a severe climate, with long-term mean temperatures below freezing and widespread permafrost.

The natural conditions in these regions are quite inclement. As a rule, the climate is sharply continental with a long, cold winter, a short summer, and brief periods of spring and autumn. The length of the frost-free season varies from 100 days in the south to a few days in the Far North. Winter low temperatures reach -60°C or below (with an absolute minimum of -72°C at Oymyakon). The long-term mean air temperature in the bleakest regions of the Yakut ASSR and the Magadan Oblast is -15°C to -16°C. Winters in some regions feature heavy fogs at temperatures below -30°C and very low temperatures combined with high winds, which make it difficult for human beings, means of transportation, and construction and other machinery to function.

The hydrological regimes of northward-flowing rivers in these regions involve an exceedingly irregular distribution of flow over the year (very low winter levels, large flood flows, and summer rainfall floods that often exceed flood levels) and very difficult conditions of ice flow, with large jams of ice 2 m or more in thickness.

In the USSR, permafrost occupies a large area, 11 million square kilometers, extending eastward from the northern European part of the Soviet Union and including much of Siberia and all of the Arctic lands. The thickness of permafrost reaches a hundred meters. An "active" layer, 0.2-3.0 m thick depending on climatic conditions, thaws in the summer.

Most of the hydraulic-power resources of the USSR are concentrated, along with major reserves of minerals and other natural riches, in the Far North, Siberia and the Soviet Far East. In the last two decades, as

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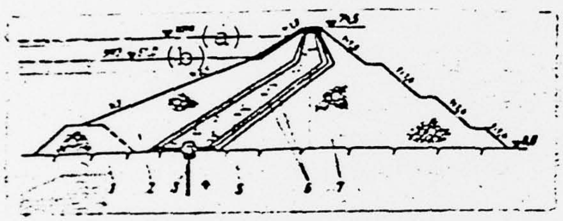
these regions have been developed, construction of hydrotechnical facilities has gone rapidly forward. At the same time as high dams have been built for hydroelectric power plants, dams with moderate and low heads have been erected. These serve the functions of supplying water to settlements and industrial enterprises and creating cooling ponds for thermoelectric power plants.

A good deal of experience in building dams under severe climatic conditions, using both earth materials and concrete, is now available in the USSR. From the 1950s on, particularly in Siberia, a number of major hydroelectric power plants have been built. Examples include the Irkutsk, Novosibirsk, Bratsk, Mamakansk, Khantaysk and other hydroelectric power plants. In 1972, construction was finished on the Krasnoyarsk hydroelectric power plant, the largest in the world, with a capacity of six million kilowatts. The plant has a concrete dam 120 m high. Earth dams already constructed (such as the one at the Vilyuysk hydroelectric power plant, Fig. 1) have attained heights of 75 m and embankment volumes of up to five million cubic meters. An earth-rock



KEY:

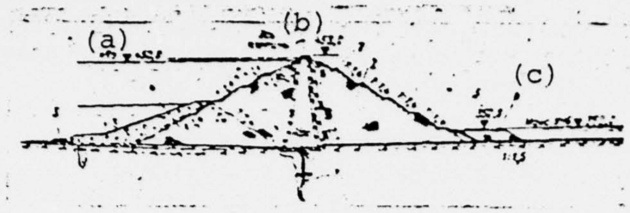
(a) Maximum water level
(b) Normal pool level

Fig. 1. Earth-rock dam at the Vilyuysk hydroelectric power plant. (1) Rockfill embankment; (2) fill; (3) grout curtain; (4) grouting gallery; (5) lining; (6) filter zones; (7) downstream shell.

dam under construction at the Kolymsk hydroelectric power plant (Fig. 2) has a height of 126 m and a volume of 12 million cubic meters. Construction is being completed on a concrete dam at the Zeysk hydroelectric power plant (Fig. 3), 115 m in height with a volume of 2.2 million cubic meters.

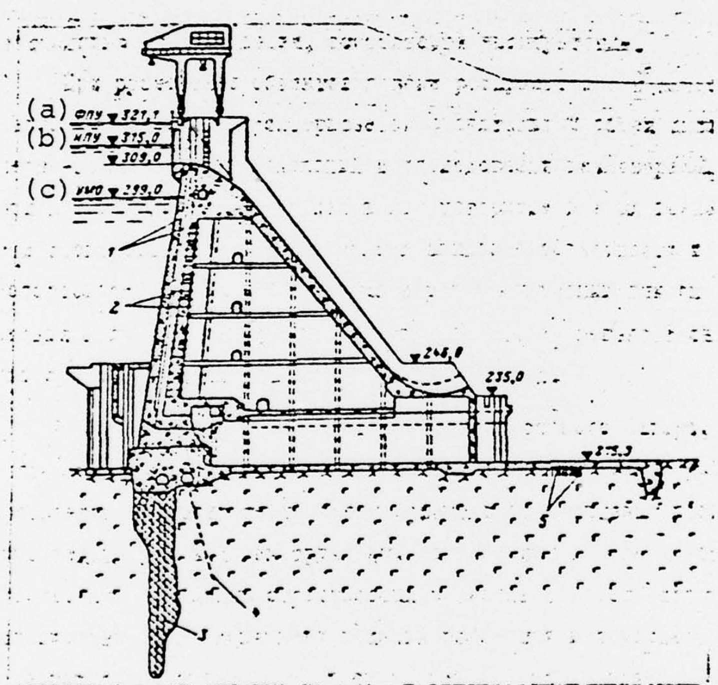
In contrast to construction in temperate regions, the erection of dams in the Far North is quite complicated.

One of the main problems that arise in managing hydrotechnical construction in the uninhabitable regions of the Far North is the difficulty of getting to these regions. No reliable, year-round means of transportation exist; the rivers are navigable only for a short period; and industrial regions are far away. These features, combined with climatic conditions adverse to life, make these regions hard to develop, so that special methods of construction, especially hydrotechnical construction, are needed.



KEY:
(a) Quite illegible, but almost certainly some pool level.
(b) Illegible
(c) First word illegible, but the abbreviation following is "lower pool level."

Fig. 2. Kolymsk dam, with impervious element of earth materials. (1) Grout curtain; (2) rockfill; (3) upstream cofferdam; (4) temporary dam; (5) downstream cofferdam; (6) waste material; (7) core from clay loam containing a crushed-rock/gruss phase.



KEY:

(a) Emergency water level
(b) Normal pool level
(c) Minimum operating level

Fig. 3. Spillway dam at the Zeysk hydroelectric power plant. (1) Seal; (2) drainage wells in supporting mass; (3) grout curtain; (4) foundation drains; (5) anchors.

Besides these management difficulties, the construction of hydrotechnical facilities involves considerable engineering difficulties. These have to do with the siting of structures on permafrost, the effects of temperatures alternating between above and below freezing, the passage of large rainfall floods, heavy ice flows, and other factors. An important

feature in the design of a dam on a permafrost layer, and the main difficulty in its construction, is the need to assure a stable thermal regime in the foundation of the dam. The thermal regime and the foundation quality determine not only the type and design of dam, but also the process used to erect it and the way in which it is operated.

When installations are sited in a permafrost zone, it is usual to do a considerable amount of engineering and geological surveying and to study the permafrost as both foundation material and construction material. These studies make it possible to settle the question whether it is possible and desirable to preserve the permafrost in the foundation or to thaw it out when the dam is in operation. This problem is often decisive in the selection of type and design of structures.

When all the problems just mentioned are taken into account, experience in construction in the Far North of the USSR indicates that, in the planning of hydrotechnical facilities, preference should go to designs that make maximum use of local materials so as to allow year-round work and minimum labor costs. Because of the high cost of shipping imported materials to remote regions of the Far North and the need to make year-round use of the work force, earth dams have gained recognition as the most economical type for these regions. Concrete dams are erected more rarely, because of their more stringent foundation requirements and the problems that often arise in the shipping of cement and the production of other concrete components.

All the foregoing has made it necessary to perform special research aimed at scientifically justifying the plans and the solutions of many design and engineering problems.

Workers in this field have developed methods for laboratory and model studies, methods of calculating temperature regimes in dams, and methods of construction that make it possible to plan and construct dams of various types, over a wide range of heads, in Far North regions.

Special value has attached to calculating the temperature regimes in earth dams. Scientific justification of planning now makes successful use of temperature calculations for the following cases in particular:

(a) Zoned earth filter dam that freezes through on account of natural cold.

(b) Zoned earth non-filter dam, with allowance for variation in the embankment and foundation temperatures during construction.

(c) Earth-rock dam, with allowance for natural air convection in the rockfill, leakage in the foundation, and thickness of snow cover on the downstream slope.

A widely-used technique is to freeze the soil for dam foundations and impervious elements. Air-cooled and liquid-cooled freezing columns are run seasonally. A method is being worked out for calculating the

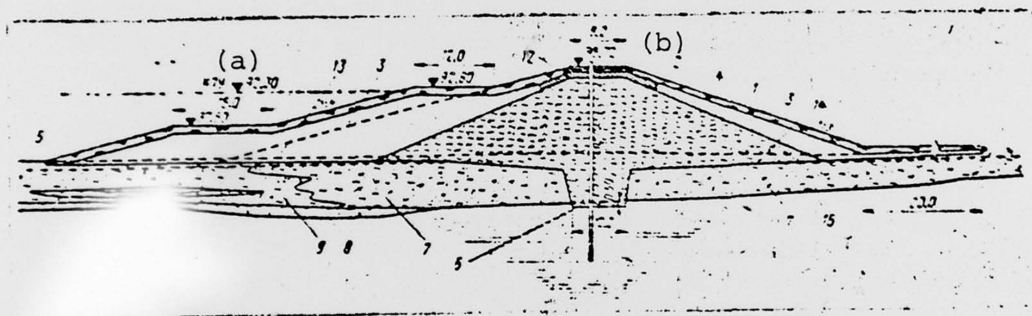
freezing of soil with freezers cooled by brine and by evaporation of refrigerants.

The planning and construction of earth dams now proceed in one of the following two ways, depending on the engineering-geological conditions and the presence of permafrost at the site:

(a) Foundation and embankment kept frozen for imperviousness and strength (frozen dam).

(b) Dam foundation and embankment allowed to thaw naturally during construction and operating period (thawed dam).

Frozen dams are constructed on foundations consisting of ice-saturated permafrost that would settle if it thawed. Freezing through of the dam embankment and talik under the stream bed and preservation (or reinforcement) of the permafrost in the foundation are accomplished with the help of freezing systems (Fig. 4, 5). Dams of this type completed and under construction are comparatively low (10-25 m).



KEY:

(a) Normal pool level
(b) -- illegible

Fig. 4. Dam on the Irelyakh River. (1) Rock slope protection; (2) peat-moss thermal insulation layer; (3) sand fill; (4) clay-loam core of dam; (5) permafrost table; (6) clay-loam cut-off; (7) silty clay loams, up to 60% ice content; (8) clay loams with marl inclusions; (9) silty sand loams with gravel and shingle; (10) sands with plant remains; (12) frozen-cutoff holes; (13) original ground level; (14) limit of removal of silts, peat and soil-vegetation layer; (15) upper limit of morainal rocks.

The selection of a design for high dams of this type from frozen soils depends on many factors, chief among them the presence and quality of borrow pits. In the Far North, dams made of clayey soils with rockfill shells have become most widespread.

In the Far North, Siberia and the Soviet Far East, local clay loams and clays are used for cores and linings in dams. These soils often occur

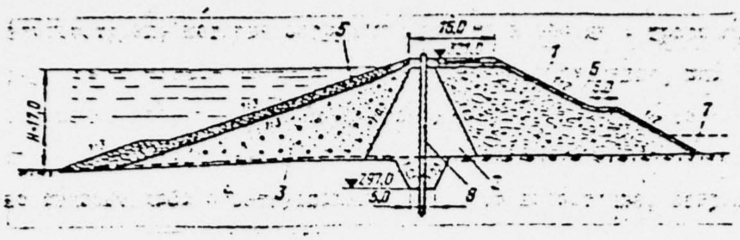


Fig. 5. Dam on the Sytykan River. (1) Rock; (2) core from clay loams with crushed-stone phase; (3) gravelly sand; (4) ground level; (5) rock slope protection; (6) insulation; (7) stream-bed backfill; (8) frozen cutoff.

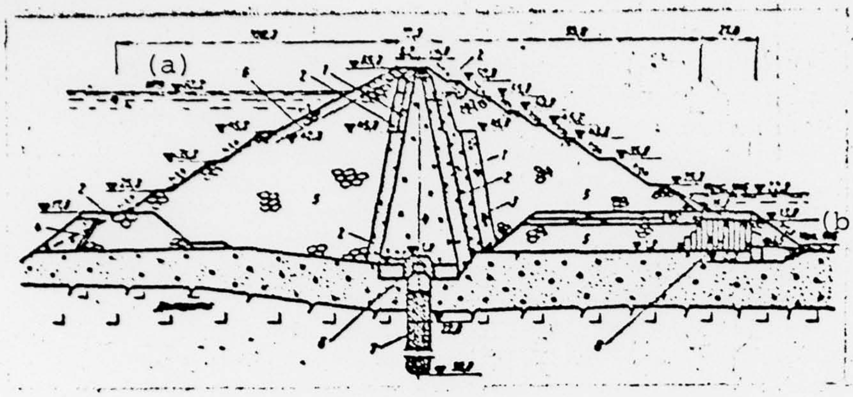
in the frozen state, so that working and placing them presents great difficulties and makes the dams expensive. For this reason, cores and linings are made relatively thin whenever possible, and embankments are made mainly from rockfill.

Year-round construction work on earth dams has required the development of special engineering methods for the extraction, storage, placement and compaction of earth materials.

Rock excavation in the northern winter is complicated by high winds and frequent fogs at low temperatures. These factors make it hard to mine and transport the soil. Problems sometimes encountered include freezing of blasted rock to the consistency of firm ground ice, making re-ripping necessary. This phenomenon usually results from either dewatering problems or contamination of the rock by fines, or from long interruptions in the work. It often becomes necessary to protect the slopes of rock excavations from falling rock. This problem is due to wide temperature swings--in particular, swings from below to above freezing in a single day, such as occur in spring and autumn--which lead to rapid weathering of the excavated rock.

Excavation work in soft soils depends heavily on the climatic conditions. These soils usually occur in the frozen state and need blasting to loosen them. If waterlogged soils lose their strength upon thawing, then it is better to work them in winter. Dewatering, coarse-rock fill under roads, and sometimes log roads are unnecessary in winter.

The following proven methods are used in hydrotechnical construction in the North for the construction of rock embankments (especially the shells of earth-rock dams). The rock obtained is not treated or dressed. It is placed without any height limitation and without special compacting. This simplified process, which improves the economics of the structure, has proved itself for central-core dams with thick transition zones (dams at the Ust'-Khantaysk and Serebryansk-1 hydroelectric power plants, Figs. 6 and 7), where the core and the upstream and downstream shells settle independently. The same method has been used for the Vilyuysk dam, a rockfill dam with clay-loam lining; no significant uneven

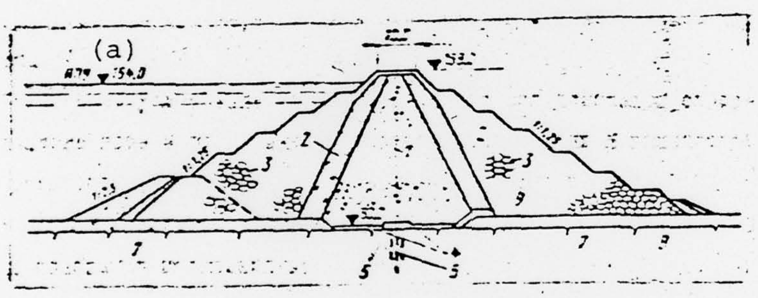


KEY:

(a) Illegible, but probably: Normal pool level

(b) Illegible, but probably meaning: lower pool level

Fig. 6. Stream-bed dam at the Ust'-Khantaysk hydroelectric power plant on the Khantayka River. (1, 2, 3) Filters; (4) core from morainal soil; (5) rockfill; (6) grouting gallery; (7) grout curtain; (8) protection of dam during flood discharge.



KEY:

(a) Normal pool level

Fig. 7. Earth-rock dam at the Serebryansk hydroelectric power plant on the Voronya River. (1) Core from sandy-loam moraine; (2) sandy-gravelly soil; (3) rockfill; (4) clay; (5) concrete slab; (6) grout curtain; (7) granites; (8) morainal crushed stone; (9) crushed stone.

settlement of the structure took place. The method has the advantage that work can continue year-round.

The placement of cohesive soils in dam cores and linings usually presents difficulties. These have to do with the shortness of the warm season, the difficulty of obtaining thawed soil of the required quality, the rapid freezing of the soil during transportation and placement in the cold season, snowfalls, and the formation of an ice crust on the surface during placement and compaction. For these reasons, a number of different procedures are used in practice.

In summer, when thawed soil of the required quality is available, the soil is either placed in layers with mechanical compaction or dumped under water with compaction by passing traffic. The second method has seen successful use in the construction of a number of dams with impervious portions from morainal soils, such as the dams at the Verkhnetulomsk and Serebryansk-1 hydroelectric power plants. At Serebryansk-1, this method was also used in the winter; steps were taken to prevent freezing of the ponds (electrical heating of the water, covering of the pond surface with polystyrene heating mats).

Soil dumped under water receives its first compaction from the dynamic action of the machinery delivering the soil, and from bulldozers used in leveling or at the surface of the layer being constructed.

Further compaction takes place through the weight of the soil itself and the action of physical-mechanical and chemical processes that occur in soil dumped under water. The effectiveness of dumping of soil under water depends on the following main points:

(1) The soil need not be wetted or dried to the optimum moisture content.

(2) Operations are simplified and compacting equipment is freed for other uses.

(3) The construction season is lengthened.

Successful field experience with dumping of soil in water has made it possible to deepen the water in the ponds, and thus to increase the height of the layer, to 12 m (dams at the Iovsk and Verkhnetulomsk hydroelectric power plants).

In the winter, at low outdoor air temperatures (to -40°C), the main method of placing cohesive soils is placement of thawed soils in layers and irrigation of the layer surface with concentrated salt solution. This treatment keeps an ice crust from forming on the soil surface. Placement and irrigation are followed by mechanical compaction. The method was used in the construction of the dam at the Vilyuysk hydroelectric power plant. It has often been described as making it possible, for the first time in world hydrotechnical-construction practice, to secure density and watertightness in an impervious dam element by dumping a clayey soil, at a moisture content near optimum and an air temperature as low as -40°C to -45°C. Clay loam containing a crushed-stone/gruss phase was used for the lining in the Vilyuysk earth-rock dam. The borrow pit lay near the dam, and working and placement in the dam were carried out by a special process. In the summer the soil was prepared for dumping. As the soil thawed, bulldozers cut it away in layers and collected it in heaps. It remained there for several days to lose moisture and build up the heat needed for winter storage. Then the soil was loaded from the heaps by an excavator and conveyed to special winter storage piles. The outer portions of the piles were salted and warmed; in the winter they were heated by electrodes. Soil prepared in

this way was recovered in the winter and transported to the dam, where it was placed in layers with compaction by type MAZ-525 machines. Irrigation with a concentrated sodium chloride or calcium chloride solution prevented the surface of the placed soil from freezing. In very cold weather, the surfaces of dumped layers were treated with exhaust gases from a type TM-59 turbojet unit ($t \simeq 500°C$) before the placement of a new layer of thawed soil. This was done to keep frozen interlayers from developing between the dumped layers.

In concrete-dam construction in the Far North, one of the basic requirements is to maintain the monolithic character and strength of the dam at all stages of construction and operation, in the face of drastic fluctuations of the air temperature.

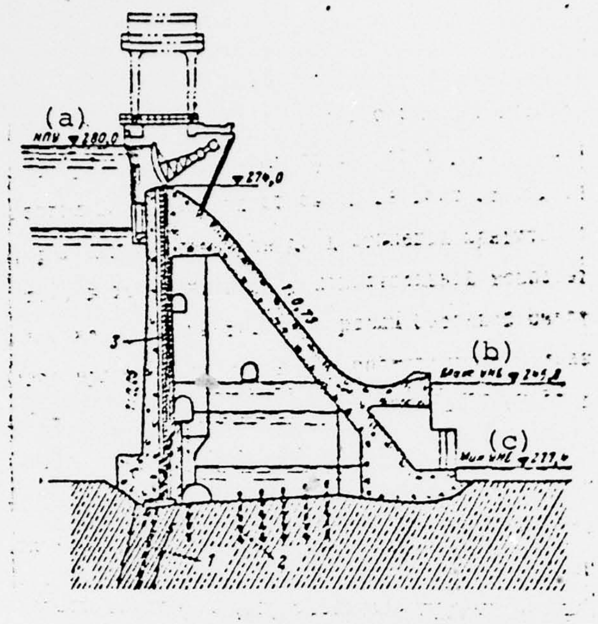
Concrete dams now under construction in the north fall into two groups by design; gravity dams and hollow dams. The first type occurs in areas with milder climates, the second under more severe conditions. The choice between types depends on how temperature fluctuations affect the stresses and strains in the dam and the opening and strength of the longitudinal joints.

Theoretical and model studies have been performed, and observations have been made on facilities under construction and already completed. As a result, it is now possible to see how an inhomogeneous temperature field affects the stress state of a structure, and to assess the importance of this factor for the state of the structure when in operation. In particular, it has been shown that freezing to a great depth in the downstream face of a gravity dam may generate considerable tensile stresses in the upstream face. As a result, deep horizontal cracks may develop, with all the undesirable consequences that this entails for the structure. This fact makes clear the additional advantages that massive-head buttress dams with enclosed recesses have over gravity dams. Holding the temperature permanently above freezing in the recesses makes it possible to limit the depth to which below-freezing temperatures penetrate from the downstream face into the supporting mass of the dam. The above-freezing temperature (0-5°C) in the recess also ensures normal performance of the dam drainage.

A similar process has provided the basis for plans for such dams as the Mamakansk dam (Fig. 8), now in operation, and the Zeysk dam, under construction, in regions where the mean annual air temperatures are -5.8°C and -4.2°C respectively. This method not only provides a satisfactory temperature regime in the structures during operation, but also lowers the cost by saving concrete.

Gravity dams can be used when (a) the temperature fluctuations do not much degrade the stress state of the dam and (b) the economy (due to the placement of mass concrete with reduced cement content and the use of simplified procedures) matches the cost of increasing the amount of concrete over the hollow design.

Of great importance for both gravity and hollow dams are the temperature



KEY:

(a) Normal pool level
(b) Max. lower pool level
(c) Min. lower pool level

Fig. 8. Spillway dam at the Mamakansk hydroelectric power plant. (1) Grout curtain; (2) drainage holes; (3) drains in supporting mass.

of the placement during the construction period, the division of the placement into blocks, the crack-resistance of the placement blocks during the construction period, and the conditions under which joinery work is performed. Calculations, research and experimental work done in the USSR have yielded the most rational size for placement blocks, the necessary temperature of the concrete during placement and hardening, methods of controlling the temperature, and methods of doing joinery work on the blocks.

The main difficulties in concrete work under severe northern conditions have to do with preventing the water in the concrete from freezing in winter. This applies at all stages of concrete mixing, placement, and hardening to the critical strength. In other words, the problem is to keep the concrete temperature above freezing. Four methods are usually used to maintain the required thermal regime of the concrete: preheating of ingredients; heating of batch plant; conveyance of concrete in trucks with warmed-up, exhaust-gas-heated beds; and the use of hot forms and heated tents over the placed blocks. Electrical heating at the periphery is also used to prevent freezing. In this process, electrodes are installed on the external surfaces of the concrete block.

Both exposed (aboveground) and covered (underground) designs are used for the construction of water-supply systems and power-plant buildings in the Far North. Covered designs are preferable from both construction and

operating standpoints. When underground facilities are sited in frozen ground, the plans must show the measures needed to prevent the harmful results of thawing.

The erection of cofferdams and the discharge of water and ice flows during the construction of water-engineering systems in severe-climate regions have, as we stated above, certain peculiarities. These have to do with the great irregularity of flow over the year, the winter low-water period, the high spring and summer-autumn floods, and the heavy spring ice flows. The ice flows are characterized by rises in levels (up to 7 m) when jams occur, and by thick, strong ice. For instance, under natural conditions the winter flows at the Zeysk and Kolymsk hydroelectric power plants drop to 7 and 0.3 m^3/sec respectively. In spring floods with a probability factor of 1%, flows may reach 14,600 and 9650 m^3/sec. The irregularity of flow over the year causes large swings, as much as 10-12 m, in the water levels.

For these reasons, stream-bed cofferdams used for the construction of hydroelectric power plants reach and exceed 30-40 m in height, and works for flow discharge during the construction period are large in size and have become complex engineering devices.

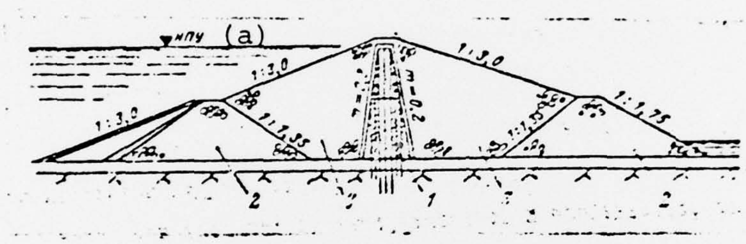
Currently, flow discharge during construction generally uses one of the following basic schemes. At earth dams, the flows are discharged through a construction trench (Vilyuysk hydroelectric power plant), a tunnel, or a concrete pipe under the dam (Kolymsk hydroelectric power plant). A combined scheme was used when the Ust'-Khantaysk hydroelectric power plant was under construction: The spring and summer floods were discharged through the unfinished stream-bed dam with a suitably reinforced downstream cofferdam, and the low-water-period flows were discharged through a temporary diversion tunnel with a relatively small cross-section. This scheme for discharging flows during construction made it possible to lower the cofferdam from 40 to 17 m, and also to dispense with the second, large, diversion tunnel. The result was a considerable saving.

Water-engineering systems with concrete dams are usually erected in two-section cofferdams when the stream is wide enough. In these cases, water is discharged through the constricted channel at first, then over the crest of the unfinished dam and through special openings at its bottom.

The passage of ice at a construction site involves considerable difficulties. When ice passes through the constricted channel, the upstream nose of the longitudinal cofferdam must be heavily reinforced, since ice may pile up against it. Quite often, the ice has to be broken up by explosions in the headrace. When ice is discharged through construction openings in concrete structures, its flow is generally held up a little. This improves the conditions for discharge of the ice, by helping the ice melt, reducing its strength, and allowing it to be carried away in high flows. Ice floes approaching a structure are usually broken up into single cakes when they enter the area of the

upstream cofferdam. These cakes, measuring 15-25 m, break up into still smaller pieces when they strike a pier; then they pass safely through openings in the crest. Experience with discharging ice through openings at the bottom has shown that definite depths must be held over the sill. The main factor contributing to the safe discharge of the ice is then the holdup of the ice flow, which (as we have shown) has a strong influence on the melting and loss of strength of the ice.

The outlook is promising for continued intensive construction of hydroelectric power plants in the northern USSR. Thus a matter of interest is the search for new design know-how and new dam materials that will be more economical and more readily produced or obtained than those now in use. Methods that use materials such as steel, polymer films and asphaltic concrete for the impervious elements in dams are quite promising. Designs of these types have been completed and are slated for experimental use. One new type of impervious element in an earth-dam embankment is the injected core (Fig. 9). A clay-cement mortar is injected under pressure through boreholes in the embankment, and the pore



KEY:

(a) Normal pool level

Fig. 9. Rockfill dam with injected core. (1) Injected core; (2) rock cofferdams; (3) upstream and downstream shells, dumped in layers.

space in the core soil becomes filled with a practically impervious material. The injection method for placing cores in earth dams will make it possible to construct dams without cofferdams in any climate.

Conclusion

On the basis of major experimental work and with the use of modern methods of calculating temperature regimes in dams, scientifically justified methods of planning hydrotechnical installations have been worked out for the Far North; basic principles have been established for the design of both earth and concrete dams; and engineering procedures have been introduced that make it possible to work year-round on dam construction.

The construction of many dams with various heads has yielded a great deal of experience and proved the possibility of successfully erecting dams under the most severe conditions in the Far North of the USSR.

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*Translator's note: The final name is poorly legible in my copy.